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Vulnerability and Feedbacks of Permafrost to Climate Change

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The effects of permafrost degradation on terrestrial and offshore environments in polar regions and on the Earth's atmosphere are significant. Field-based observations, remote sensing, and modeling document regional warming and thawing of permafrost. However, major research questions regarding vulnerability of permafrost to thawing, the projected decline in permafrost extent during coming decades, resulting ecosystem feedbacks, and the possibly global consequences to climate change due to remobilization of carbon pools from thawing permafrost still require answers.

Permafrost Warming, Resilience, and Vulnerability

Permafrost, defined as ground that remains below 0°C for at least two consecutive years, may comprise bedrock, sediment, soils, or organic materials and may or may not contain ground ice. Of particular significance are the 2 million square kilometers (or 8.8%) of the total Northern Hemisphere permafrost region (22.8 × 10⁶ square kilometers) that have ice-rich permafrost (>20% excess ice content) in the upper 10 meters [Zhang et al., 1999] (see Figure S1a in the online supplement to this *Eos* issue (http://www.agu.org/eos_elec)). Though all permafrost can be affected by warming and thawing, thawing of ice-rich permafrost causes particularly strong feedbacks to ground surface stability, microtopography, hydrology, ecosystem function, and the carbon cycle [Rowland et al., 2010].

The Thermal State of Permafrost (TSP) monitoring initiative includes 850 boreholes and 200 active layer sites and shows a general warming trend for the upper permafrost in many Arctic regions throughout the 1990s and early 2000s, in accordance with air temperature trends [Romanovsky et al., 2010]. Warming has been more pronounced in the northern continuous permafrost zone, most recently along the Arctic coast. The warming of cold permafrost in the continuous permafrost zone generally has not resulted in thawing during the past 60 years, while similar warming in some discontinuous

permafrost regions, such as European Russia, has resulted in widespread thawing.

The vulnerability and resilience of permafrost to climate warming, however, is complicated by dynamically changing surface properties related to snow, vegetation, active layer thickness, surface water, groundwater, and soils. Remarkably, these dynamics can lead to both positive and negative feedbacks to permafrost stability, allowing permafrost to persist at mean annual air temperatures (MAATs) as high as +2°C along the southern margin of the permafrost and to degrade at MAATs as low as -20°C in the High Arctic [Jorgenson et al., 2010]. For example, negative feedbacks from these interactions primarily related to vegetation succession can reduce mean annual soil temperatures by as much as 6°C. In contrast, surface water can raise temperatures at the water-sediment interface by as much as 10°C, rendering permafrost vulnerable to thawing even in cold Arctic environments.

These feedbacks have affected permafrost over long time periods. Ice-rich permafrost from before the last interglacial (>130,000 years ago) persists today even though the last interglacial and the Holocene thermal maximum (HTM; ~5000–11,000 years

B.P., depending on region) were up to several degrees Celsius warmer than present in many northern regions [Reyes et al., 2010]. The thermal inertia of ice-rich ground; rapidly evolving topography and drainage networks that prevent water impoundment; and development of thick organic soils, mosses, and a vegetation canopy helped to protect permafrost from thawing. Much of discontinuous and sporadic permafrost that is currently vulnerable to thawing was formed during the Little Ice Age (LIA; circa 1650–1850 C.E.). Climate warming since the LIA caused permafrost extent to approach pre-LIA levels again. Spatially explicit modeling indicates that permafrost could shrink below the minimum extent reached during the HTM by 2100, as permafrost with temperatures currently between 0°C and -2.5°C will be actively thawing, affecting almost half (9.0 × 10⁶ square kilometers) of the current permafrost extent in the Northern Hemisphere [Romanovsky et al., 2008].

Such projections of the future state of permafrost are based largely on subsurface thermal dynamics driven by regional or global climate model projections and internal surface and ground properties. However, subgrid-scale feedbacks associated with the aforementioned dynamic ecological components and disturbances are not considered. Soil removal and disturbances of the ground thermal regime triggered by fires, floods, and vegetation can result in rapid local

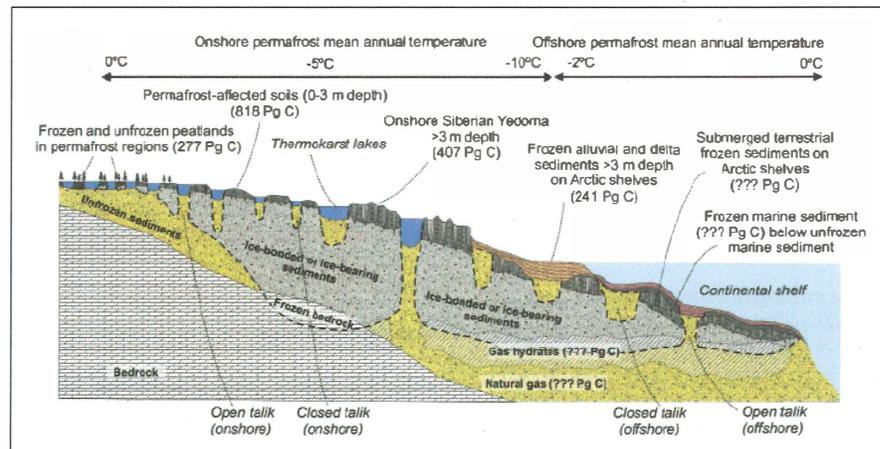


Fig. 1. Idealized cross section through northern permafrost regions showing the major known and assumed carbon pools related to permafrost and their total carbon stores, in petagrams as known to date (adapted from Romanovskii et al. [2000]; soil organic carbon stores from Tarnocai et al. [2009]). Question marks indicate poorly quantified carbon stocks. Original color image appears at the back of this volume.

degradation of permafrost by thermokarst or thermoerosion. Though local in nature, disturbance processes are widespread regionally. The occurrence and magnitude of some disturbance processes, such as fire or thermokarst, are likely to increase with climate warming in the Arctic, thereby accelerating permafrost degradation.

Feedbacks to Carbon Pools and Climate

Surface thawing of permafrost, as well as deep degradation after disturbances, is affecting organic carbon pools in permafrost. When the organic matter stored in permafrost-affected soils and deeper permafrost deposits is taken into account, the estimated 1466 petagrams of organic carbon contained in Arctic terrestrial permafrost soils is enormous relative to atmospheric stocks [Tarnocai *et al.*, 2009] (see Figure S1b in the online supplement to this *Eos* issue). A generalized north-south permafrost cross section shows the size and distribution of carbon pools in and under permafrost (Figure 1). However, high uncertainties related to soil spatial distribution and depth, organic carbon content, and organic matter lability remain. Several other permafrost-related carbon pool components are also lacking tight constraints: organic carbon stored in submerged terrestrial and marine permafrost deposits on Arctic shelves, gas hydrates stored in and under permafrost, and natural gas capped by permafrost. Of particular concern is a unique, ground ice-rich surficial deposit in Siberia and northwestern North America called "Yedoma" that alone is estimated to contain more than 400 petagrams of organic carbon (Figure 1) [Zimov *et al.*, 2006].

Top-down thawing of permafrost will cause major changes in soil carbon cycling over large regions and tap permafrost-related organic carbon pools [Schuur *et al.*, 2008]. While mineral soils often experience rapid carbon loss, peat accumulation rates and methane emissions may increase as organic soils thaw. Biological production of greenhouse gases from Yedoma-like deposits upon thawing is a potentially strong positive feedback to climate warming. A multitude of permafrost degradation processes can affect deeper carbon pools, with the potential to weaken this long-term carbon sink or even to create a carbon source.

Thermokarst and Other Forms of Deep Degradation Affecting Organic Carbon Pools

The melting of excess ground ice, including segregated ice, ice wedges, and other massive ice bodies in permafrost, results in subsidence and water impoundment. Thermokarst lakes, whose positive feedbacks accelerate subsidence and permafrost thaw, formed during the Holocene (the past 12,000 years) and are widespread in Arctic lowlands (see Figure S1a in the online supplement). They mobilize deeper permafrost-stored organic carbon and enhance greenhouse gas emissions [Walter *et al.*, 2007].

Future thermokarst lake dynamics (drainage or growth) will affect methane emissions and carbon sequestration and thus permafrost-carbon cycle feedbacks. Changes in thermokarst lake extent observed during recent decades show both increases and decreases in area depending on region.

Other processes also degrade permafrost and mobilize deep soil organic carbon. Most of the modern Arctic coast and many riverbanks are affected by thermoabrasion of icy permafrost sediments. Permafrost coastline retreat rates sometimes exceed 20 meters per year [Jones *et al.*, 2009]. Erosion rates are likely to accelerate with permafrost warming, increased seawater temperatures, and reduced sea ice extent. In addition, thermal erosion causes mass wasting in gullies, retrogressive thaw slumps, and active layer detachment slides.

Methane trapped in and below degrading subsea permafrost on the Arctic continental shelves, which was formed when the shelves were exposed by a low glacial sea level stand (Figure 1), may be released. Although the spatial and temporal scale of organic carbon pools in terrestrial shelf sediments and their vulnerability to climate warming are poorly understood, elevated concentrations of dissolved methane in the East Siberian Sea suggest that these carbon pools are mobile [Shakhova *et al.*, 2010].

Future Research

During the International Polar Year 2007–2008, integrated projects such as the TSP, Carbon Pools in Permafrost Regions (CAPP), and Arctic Circumpolar Coastal Observatory Network (ACCO-Net) investigated permafrost and the impacts of its degradation. Despite accumulating knowledge of permafrost dynamics during Quaternary (the past 2.58 million years) climate cycles, of large and climate-sensitive carbon pools in permafrost, and of the widespread occurrence of thermokarst in northern regions, many processes remain poorly quantified on the pan-Arctic scale. To make progress, researchers from various disciplines must team together to understand the patterns, processes, time scales, and consequences of permafrost thaw to the Earth system. Focus areas of research to improve understanding include better description of permafrost characteristics (i.e., thermal state and ground ice content), extended field documentation and modeling of permafrost-vegetation-hydrology-climate feedbacks across spatial and temporal scales, and determination and quantification of the role and vulnerability of permafrost-related organic carbon pools in the Earth system.

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